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Evaluating Ecological Sustainability For The Planning and Operations Of Storage Technologies

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Abstract

With an expected future increase of costs for carbon emissions the logistics industry is targeting to design sustainable warehouses to reduce their carbon footprints. To do so, it is required that every aspect of a warehouse from its general design to the transport processes and technologies must be assessed in terms of its carbon footprint. In this article the carbon footprint, which can be traced back to the storage technology employed within a storage area is analysed. The approach includes surface, material, and technology-related data to calculate the carbon footprint of a logistics concept. Firstly, different dimensions of storage technology carbon footprints are identified. A comprehensive model is provided to calculate the carbon footprint of alternative storage technologies in a warehouse. The model is applied in a case study with actual data from a warehouse planning project in the German production industry comparing three alternative storage technologies for a small part storage solution. The author's find highest carbon footprint in the application of an autonomous guided vehicle shelving system compared to automatic storage and retrieval system and manual storage solution using Kanban racks.

Keywords

Warehouse planning; Ecological sustainability; Storage technologies; Carbon emissions

1. Introduction

Warehouses are substantial parts of global supply networks, as they build the main interface between an organization's supply, its production, and its interface to the customer. Global uncertainties in supply chains, however, have led organizations in production and e-commerce to increase their stocks preventing future supply bottlenecks resulting in the need of more storage areas. In Germany, the warehouse capacities have increased by 19 % within one year [1]. The recent rising demand of storage surface enhances the need of new and larger logistics hubs and the efficient use of the existing logistics technologies. Planning and designing these new warehouses, the major targets are the implementation of efficient material flows and storage concepts to achieve the highest decrease in storage and transport costs.

Besides the strive for economic efficiency, the contribution of logistics to greenhouse gas emissions has gained attention [2]. According to Doherty & Hoyle [3] a substantial amount of 11% of the total greenhouse gas emissions from logistics can be traced back to warehousing and its operational activities. As costs for greenhouse gas emissions raise [4], designing and building ecologically sustainable warehouses will become a competitive factor throughout economy. Therefore, the assessment of ecological sustainability of a warehouse building as well as its processes and storage technologies is to be integrated into the planning of new warehouses.

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Assessing the sustainability of buildings has been subject to many investigations recently [5,6]. However, the sustainability analysis of storage technologies within warehouses is limited. Hence, the objective of this research is to develop a model to assess the ecological sustainability of different storage technology scenarios for newly designed warehouses. Two research questions are explored to satisfy this objective:

- RQ1: Which dimensions are to be considered to assess the carbon footprint of storage technologies?
- RQ2: How can the carbon footprint of different storage technologies be calculated to compare different alternatives in terms of their ecological sustainability?

For the assessment of the above research questions the analysis concept and model are applied on data of a practical warehouse planning project, comparing three different storage technology concepts in terms of their carbon footprints for the chosen storage technology in a case study.

First, an overview of the existing literature about the sustainability assessment of storage technologies and warehouses is given. The article continuous with the introduction of a concept for an model to analyse the respective carbon footprint for a given storage technology. The developed and implemented model is then applied to three planning scenarios of a warehouse planning project to compare the carbon footprint for each storage technology. The article closes with a conclusion, its limitations, and an outlook for further research in the field of warehouse sustainability assessment.

2. Related literature

Traditional logistics and material flow planning methods with a focus on warehouse planning projects follow strict planning stages [7]. Within these stages, warehouse concepts will be developed by defining the project scope, conducting data analysis, developing a planning baseline (processes, system boundaries and dimensioning of storage technologies), elaborate a detailed logistics concept and a final realization of the project [8]. These warehouse concepts often consist of invest and operational budgets, material flow definitions, surfaces, and layouts as well as the integration of qualitative criteria by benefit value analyses [9]. More recent planning approaches also focus on the integration of stakeholders and managing uncertainties within the planning [10]. None of these approaches explicitly include parameters to evaluate the sustainability of alternative planning scenarios.

Existing evaluation frameworks for calculating the carbon footprint resulting from storage technologies in warehouses focus on evaluation criteria and emissions resulting from the warehouse operations. In a study conducted by Torabizadeh et al. [11] evaluation criteria are collected from existing literature and weighted for a utilization in sustainability assessments. The weighting of criteria was done by expert interviews and questionnaires. In this study criteria from all sustainability fields (ecologic, social, and economic) are included. Another study proposes an evaluation approach with a focus on the carbon emissions resulting from the warehouse operations [12]. It includes lighting as well as heating, cooling, and ventilation (HVAC). The operative emissions are further investigated in terms of energy consumed by transport technologies to maintain warehouse operations in the storage technologies. The work of Lewczuk et al. [13] proposes another calculation method to estimate the energy consumption resulting from the warehouse operations in different storage technologies. Here, the dimensions HVAC, lighting, IT systems and operations are considered. Indices, which indicate the share of automated storage technologies and the share of energy from photovoltaic systems, are included. Further studies investigate the energy consumption of different warehouse equipment in existing warehouses and integrates the costs of carbon emissions [14,6,15]. The detailed view on the energy consumption of transport technologies is also investigated in the literature. Energy consumption estimations were performed for operations with forklift trucks [16,17] and transports performed by mini load cranes in automatic storage and retrieval systems (ASRS) [18–20]. Other specific investigations were performed on the heating and temperature distribution in high warehouse buildings [21–23]. The reviewed studies show evaluation frameworks for operative energy consumptions and carbon footprints of warehouses as well as analyses of historic energy consumption in existing warehouses.

General literature reviews on sustainable warehousing regard trends and future research demands in the field of sustainability assessments. The study of Bartolini et al. [2] states that carbon emission taxes will influence warehouse operations in the coming years. Further, they define research demands for measures of warehouse sustainability to highlight optimization potentials, conducting case studies based on empirical data, evaluation models for carbon emissions and smart lighting systems. The investigations of Udara Willhelm Abeydeera et al. [24] support these demands by the need for tracking and predicting carbon emissions as well as identifying optimization and mitigation potentials. According to Bank & Murphy [25] research on metrics, standards and guidelines for sustainable warehousing is demanded. Further research on sustainability in logistics is performed in the areas of building and transport emissions. In the field of transport emissions analytical models and simulations studies are available [26,27]. The field of building emission research is conducted to estimate carbon emissions resulting from the construction activities of warehouse buildings [5]. From the literature, a clear demand for new and revised models for estimating the sustainability of future warehouses in early stages of planning projects can be extracted.

The existing literature presents a variety of approaches for estimating the carbon emissions or energy consumption in warehouse planning projects. The dimensions of these approaches cover the major operative emissions by considering transports, HVAC, and lighting. To the best knowledge of the authors, none of these approaches includes the emissions resulting from the installation of storage technologies in warehouses. Further, existing approaches are quite extensive and not always applicable in warehouse planning projects due to data availability and project timelines.

3. Concept of a model for determining carbon emissions resulting from storage technologies

To address the gaps in the existing literature, this section proposes a new concept and an analytical model to assess the ecological sustainability of alternative storage technologies within warehouse planning projects (Figure 1). In contrast to existing literature, the ecological sustainability of different planning scenarios is assessed by determining the carbon footprint in the construction and operation of storage technologies. The model is designed as an analytical model to estimate future carbon footprints of warehouses in early planning phases with limited data input. The model requires a fixed set of input parameters, which provides a baseline for subsequent evaluation steps. The evaluation of alternative storage technologies is performed under consideration of the dimensions heating, lighting, additional building construction, operational and storage technology production emissions. The output values can be converted to total carbon emissions for construction and operations using carbon equivalents for the different energy sources consumed.

The model input is separated in three categories. (1) Building-related information form the first category. Here, surface and heating demand in the different storage areas are required. (2) SKU (stock keeping unit)-related information are parameters determining the storage conditions required by the materials and parts to be stored. This category contains the storage technologies, locations required and lighting demands. (3) Dynamic data are required for determining the in- and outbound movements to be performed within the storage areas using respective transport technologies like forklift trucks or ASRS shuttles. Storage technology-related information includes the raw materials to produce the structural components of the racking and control technologies. Further, the steps within the production process need to be available as well as transports efforts performed within the production process.

The first dimension of evaluation is the calculation of heating emissions. Here, the heating energy per storage area is determined. Second, the determination of the lighting energy emissions is included by calculating the number of required headlights. As some technologies require additional surfaces, the category additional building construction emissions identifies these construction emissions. The major operational emissions result from the movements of goods. Using dynamic data, the energy consumption per movement of applied transport technologies (e.g., ASRS, conveyer, or forklift trucks) is analysed. For storage technology emissions the evaluation includes carbon emissions of the raw materials (e.g., steel), the different production processes. Further, transport efforts and packing materials for production and transhipment are utilized.

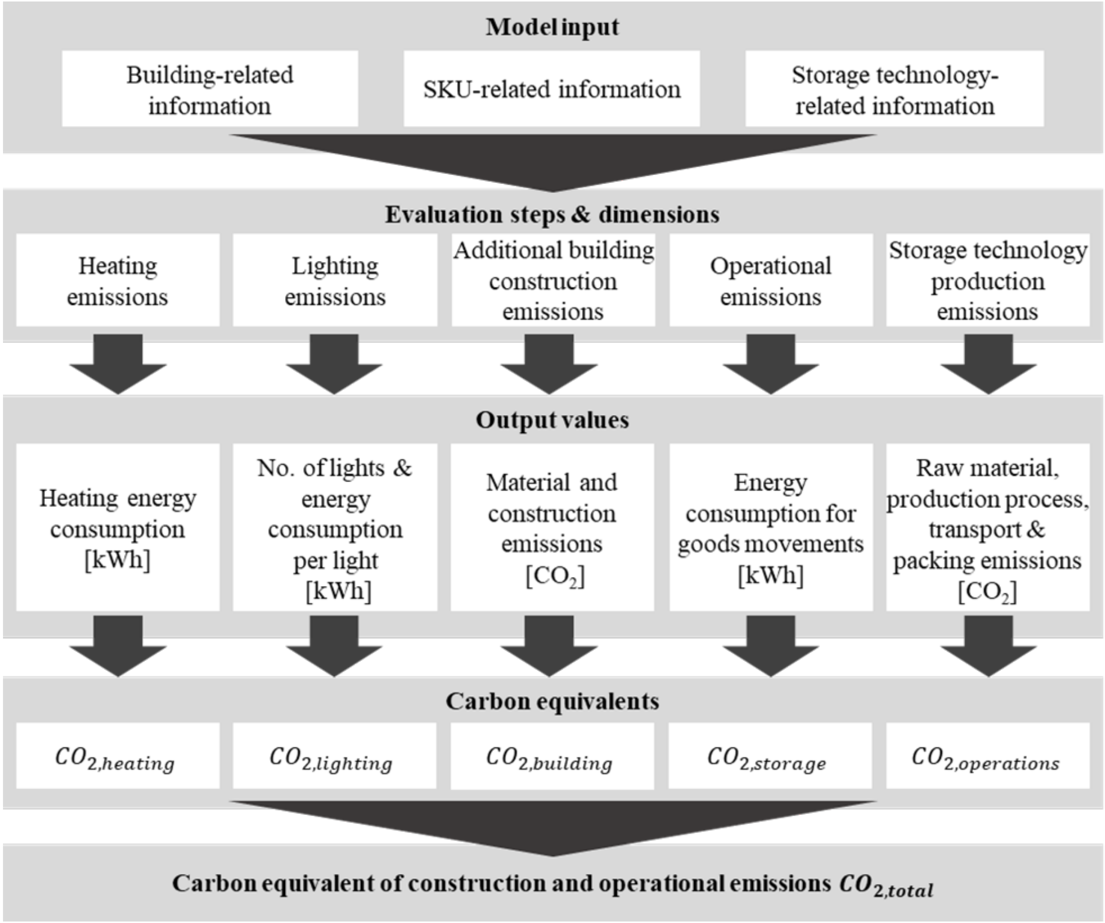

Figure 1: Concept of the calculation model from carbon emissions resulting from storage technologies.

Finally, the model attributes all individual dimensions to a single measure

$$CO_{2,total} = CO_{2,heating} + CO_{2,lighting} + CO_{2,building} + CO_{2,storage} + CO_{2,operations} \qquad (1)$$

in the form of carbon emissions. If the single dimensions cannot directly provide a carbon emission value, equivalents will be applied to convert energy consumptions to carbon emissions [28]. In this manner, the model can provide a single and central value which allows users to compare the carbon emissions of different planning scenarios and determine the influences of the different technologies and dimensions within the model. Further, all values are based on actual energy and emission data.

In the remaining part of this section, the calculation steps to evaluate the emissions in the five dimensions are described. The **heating emissions** are mainly based on the calculation of the heating load to maintain a given temperature. The calculation results in the energy consumed to maintain the temperature and can be converted to an equivalent value of the corresponding carbon emissions. This calculation requires an input of the geometric dimensions of the warehouse and the storage height, which is to be heated. Further, energy consumption is highly depended on the heating system installed in the warehouse and the regional environmental conditions of the warehouse location. Operational data is utilized to integrate the operational hours and working days of logistics operations in the warehouse. The heating load

$$E_{heating} = E_{sqm} * A_{surface} * t_{operations} \tag{2}$$

calculates the heating energy for the utilized surface in kilowatt hours per year. This calculation was adapted and simplified from Lewczuk et al. [13]. E_{sqm} represents the energy to maintain the given temperature at one square meter (sqm) in the warehouse at a given storage height. $A_{surface}$ is the surface of the warehouse to be heated. The operational hours per year are given by $t_{operations}$. The calculation of the carbon footprint

$$CO_{2,heating} = CO_{2,heating,kWh} * E_{heating} \tag{3}$$

is performed by using a carbon equivalent value $\mathrm{CO}_{2,\mathrm{heating,kWh}}$ per kWh in the given country.

The calculation of **lighting emissions** is performed by considering the lumens required per surface area. Thereby, the total amount of lights required can be calculated and traced back to the consumed electric energy. The calculation of required electric energy for lighting

$$E_{lighting} = \sum_{i=1}^{n} \frac{A_i * l_i}{l_{light}} * E_{light} * t_{operations} \tag{4}$$

starts with the calculation of the of required lights per storage area. A_i defines the surface of a given storage area i, l_i integrates the required lumens per sqm within the storage area and l_{light} is the number of lumens delivered by a single light. Including the electric energy per light E_{light} and the operational hours $t_{operations}$ the electric energy for lighting in all storage areas n is calculated. Using the carbon equivalent for electric energy the total carbon emitted by lighting $CO_{2,lighting}$ is determined.

The calculation of **additional building construction emissions** is realized by accounting the emissions for the raw material and the construction by carbon equivalent values. The calculation of raw material emissions

$$CO_{2,building} = \sum_{j=1}^{m} \sum_{k=1}^{o} CO_{2,material,j,k} * V_{i,k} \tag{5}$$

integrates all storage areas which require specific building facilities m and all materials o utilized within the construction process. The carbon equivalent value $CO_{2,material,j,k}$ represents the carbon emissions of one volume unit of a specific material utilized in the construction. $V_{i,k}$ is the volume of the specific material used in the building process.

The calculation of **emissions resulting from the storage technology installations** itself are determined by the emissions of included raw materials, production processes of the storage technologies, transports and used packing materials (Figure 2).

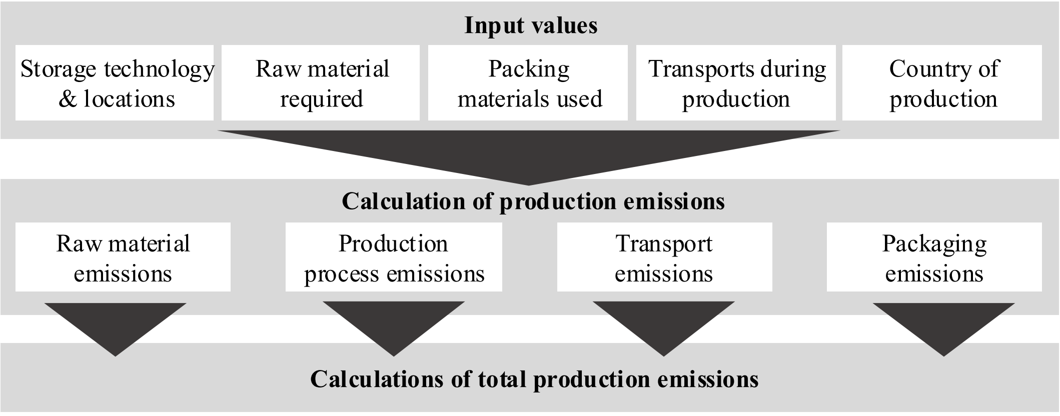

Figure 2: Calculation process for determining the production emissions

The emissions from raw materials for all storage technologies m and all applied materials o is determined by material quantity per unit of a given storage technology.

$$CO_{2,materials} = \sum_{j=1}^{m} \sum_{k=1}^{o} Q_{material,j,k} * CO_{2,material,j,k} * Units_{m} \tag{6}$$

The carbon equivalent $CO_{2,material,j,k}$ specifies the carbon emissions per ton of the respective material quantity $Q_{material,j,k}$. These values are multiplied with the number of units of a storage technology required in a planning scenario. The production emissions

$$CO_{2,production} = \sum_{j=1}^{m} \sum_{k=1}^{o} Q_{material,j,k} * CO_{2,production,j,k} * Units_{m} \tag{7}$$

are calculated in accordance with the calculation of emissions from raw materials (6) except the carbon equivalent value $CO_{2,production,j,k}$ for a specific production process required in the manufacturing of a storage technology. The transport emissions

$$CO_{2,transport} = \sum_{j=1}^{m} d_j * CO_{2,km} \tag{8}$$

for all storage technologies m is determined by the traveled distances d_j and a carbon equivalent value $CO_{2,km}$ of the acquired transport mode. The emissions from packing material for all storage technologies m and all applied packing materials o

$$CO_{2,packing} = \sum_{j=1}^{m} \sum_{k=1}^{o} Q_{packing,j,k} * CO_{2,packing,j,k} \tag{9}$$

are determined by the quantity of all utilized packing materials $Q_{packing,j,k}$ and their respective carbon equivalent value $CO_{2,packing,j,k}$.The total carbon emissions resulting the utilized storage technologies are given by the sum of all sub calculations.

$$CO_{2,storage} = CO_{2,materials} + CO_{2,production} + CO_{2,transport} + CO_{2,packing} \tag{10}$$

The **operational emissions** are highly dependent on the applied storage technology, distances to be travelled in a warehouse for the picking and replenishment process as well as dynamic data regarding the in- and outbound. The storage technologies define the transport technologies utilized within the picking and replenishment process. Here, the emissions vary from manual transports, which do not directly lead to carbon emissions as no energy is consumed to perform the processes, to fully automated storage technologies. ASRS' perform all transports by picking robots and conveyor systems with significant consumptions of electric energy. The dynamic data of the in- and outbounds defines the quantity of transports to be performed within the storage technologies. As the calculation of the operational emissions $CO_{2,operations}$ is highly dependent on the storage technologies, this work cannot provide a generic approach to determine the carbon emissions of transport technologies. Therefore, the calculation of operations emissions must be specified within in planning projects according to the storage technologies to be designed.

The total carbon footprint $CO_{2,total}$ is calculated by the sum of all sub steps within the model. Thereby, this work proposes an approach which enables logistics planners to estimate future carbon footprints resulting from storage technologies in warehouse planning projects. The model concept comprises emissions determined by the construction of the storage technologies as well as emissions of the operations of the future warehouse for a certain period of investigation.

4. Case study – Comparison of small part solutions from a practical warehouse planning project

This section aims to describe the relationships between the chosen dimensions of the proposed model and the overall carbon footprint of small part storage technologies in a future warehouse on the basis of the research procedures for explanatory case studies [29]. The case was selected based on an anonymous dataset resulting from a practical planning project of a warehouse to secure the supply of a production site. Therefore, a storage inventory analysis and acquisition of dynamic data regarding the goods movements in the warehouse was performed. This forms the baseline for the calculation of future storage locations and surface demands.

Three scenarios of a small part storage solution including an ASRS, a fully manual Kanban rack area and an autonomous guided vehicles (AGV) shelving system are compared. The ASRS scenario can be integrated in a one storied warehouse. The remaining scenarios required a second floor due to higher surface requirements and low utilization of the available height. Table 1 presents the basic planning parameters of the project. The model considers the required surface calculated from storage capacity requirements, building surfaces, which is required to construct the system, transport technologies to maintain operations, the major production steps to process the raw materials and the amount of raw steel needed to produce the racks.

Table 1: Parameters of the planning scenarios

Scenario	Surface [sqm]	Add. building surface [sqm]	Transport technology	Energy consumption [kWh]	Production processes	Raw material volume [t]
ASRS	350	0	Mini load	1.78	Hot rolling, coating	52.5
AGV-shelving	1400	1150	AGVs	3.2	Hot rolling, coating	26.5
Kanban racks	1400	1150	Manual	0	Hot rolling, coating	32.6

For all planning scenarios, general input parameters serve as underlaying conditions. In the future warehouse a heat pump heating system is applied to maintain a temperature of 20°C up to a height of 4.8 m. This leads to an electricity consumption of 80.72 kWh per year and sqm [13]. The carbon equivalent values were taken from available data on the energy share in Germany [28]. The amount of required light intensity is assumed at 300 lumens per sqm. The operational hours were assumed as 4,200 h per year. To calculate operational emission dynamic data from the current warehouse was analyzed. On average, the system is required to fulfill 700 storage movements per day.

The results of the model (Figure 3) show the carbon emissions of the planning scenarios for the construction emissions (production and additional building emissions) and recurring emissions within 10 years (heating, lighting, and operational emissions). With a total of 525 tons of CO_2 the ASRS system shows the lowest carbon footprint compared to a manual Kanban rack zone (780 tons of CO_2) and the AGV-shelving (860 tons of CO_2). Amongst all scenarios, significant differences are indicated for the production emissions and for the heating emissions. With the highest amount of raw material to be processed, the ASRS indicated the highest carbon footprint in production (steel bar construction). As the ASRS solution can be integrated into a one story building no additional building surface required.

The scenario AGV-based shelving system leads to the highest overall emissions as a large-scale area is to be heated and the amount of raw material required for production. Across all scenarios the production, additional building (concrete) and heating emissions are the major contributors to the overall emissions. It can be obtained that on the one hand automation leads to higher emissions in the production of the storage technologies. On the other hand, the long-term emission savings for heating can be expected with lower surface demands. These investigations can be used when it comes to the mitigation of fixed emissions from the construction of storage technologies and the amount of electric energy required from renewable energies to maintain low emissions in operations. The implementation of highly densified storage systems is expected to decrease the overall carbon footprint of a warehouse can therefore enhance the ecological sustainability. This work is based on a practical and ongoing planning project. For this reason, a validation by actual emission measurements is a task for future research activities.

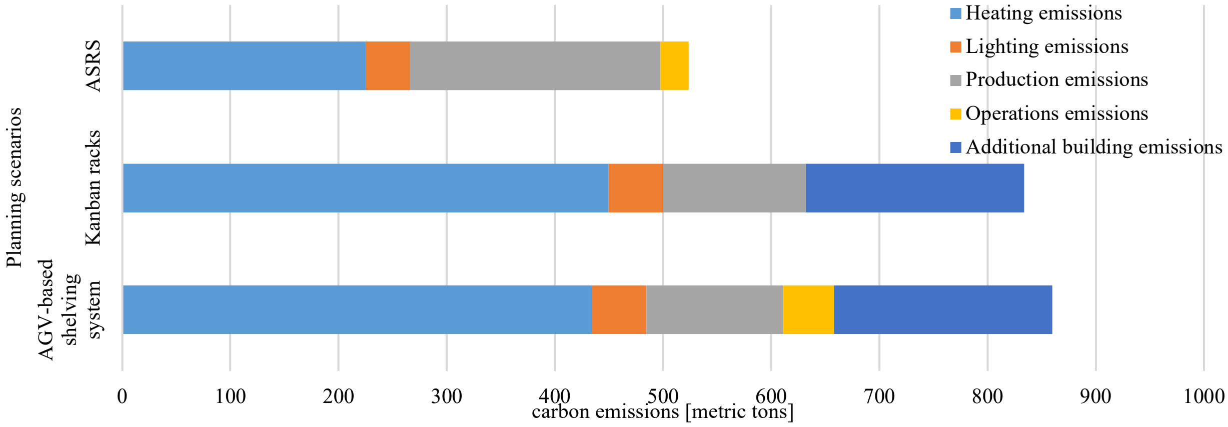

Figure 3: Carbon emissions calculated over a period of 10 years

5. Conclusion and outlook

The proposed model is a data-based method to be applied in the early planning phase of a logistics concept to estimate future carbon emissions. The model provides an approach to assess the carbon footprint of alternative storage technologies in warehouse planning projects. According to RQ1, the approach combines the dimensions heating, lighting, additional building, operational and production emission in a comprehensive calculation method. These dimensions cover the emissions resulting from the construction and production of storage technologies as well as emissions of the warehouse operations. Within the dimensions, the model allows the comparison of alternative storage technologies by determining the energy consumptions and applying carbon equivalent values in a structured approach (RQ2). The combined emissions calculated for each storage technology indicate the overall carbon footprint per planning scenario. To carry out this evaluation building-related, SKU-related and storage technology-related inputs are needed.

The model was applied on a dataset resulting from a practical warehouse planning project to compare competing storage technologies for small parts in standard boxes. The results show a lowest carbon footprint for an ASRS solution and a highest footprint for an AGV-based shelving system. The major reasons were the low heating emissions in the ASRS scenario due to smallest building surface required by the utilization of the full storage height, the additional building surface required for AGV-based shelving system and Kanban racks. From these investigations, it can be noted that automated solutions with high surface densification can result in a lower overall carbon footprint. With rising costs for carbon emissions, the lower carbon footprint systems like ASRS might have an impact on investment decisions in the planning phase of warehouses.

For practical applications, this work offers a manageable and structured approach for accounting carbon footprints to alternative storage technologies. It can serve as a decisions support when it comes to the selection of a preferred planning scenario. The model opens the possibility to explore optimization potentials for operational emissions (lighting, heating, and operational transport emissions). Mitigation potentials (e.g., renewable energy sources) can be illustrated for emissions for additional building and production as these cannot be directly influenced.

However, the model is limited as sustainable logistics warehouse includes further aspects e.g., energy sources and waste management. Further, the market of storage technology for a specific type of SKU is very diverse with a manifold of different suppliers, providing different production and distribution methods. Due to very specific building electronics and machinery components like AGVs and conveying machines, a method of their dedicated carbon footprint cannot be delivered by this approach. To further validate the assumptions and calculations determined in this article, the sample size of case studies should be extended and more storage technologies for big and palatized parts must be included.

Future research activities will focus on applying the approach in further warehouse planning projects and thereby increase the sample size of available use cases. The model will be extended in terms of the production emissions to include further materials and processes especially for electronic components in storage technologies. It is planned to improve the validity of the model by simulation studies.

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Biography

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Jochen Kreutzfeldt, Prof. Dr.-Ing. (*1959) is Professor and Head of the Institute for Technical Logistics at Hamburg University of Technology. After studying mechanical engineering with a focus on production engineering, Jochen Kreutzfeldt held various executive positions within a company specializing in automotive safety technology. Subsequently, Jochen Kreutzfeldt took over a professorship for logistics at the Hamburg University of Applied Sciences as head of the Institute for Product and Production Management.